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Feasibility of a wearable, sensor-based motion tracking system

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Abstract

The objective of this study was to develop and evaluate the feasibility of a wearable, sensor-based motion tracking system that provides an economical and quantitative means of recording upper limb motion for physical rehabilitation. The tracking system is comprised of a wirelessly connected network of inertial measurement units (IMUs), each containing a gyroscope and an accelerometer. Two IMUs were rigidly attached to each subject's forearm and upper arm. A trajectorizing algorithm was developed to estimate the three dimensional upper limb motion based on the measurements of the IMUs. A major advantage of the algorithm is that it allows the IMUs to be attached with arbitrary orientation to each limb and no manual anthropomorphic measurements need to be performed. By recording specific, known motions, the sensors can be calibrated with respect to their orientation in space and with respect to their orientation relative to their respective body segments. During the experiment, healthy subjects performed elbow flexion-extension motions that were recorded using the IMUs. To validate the system including the accuracy of recorded data and the correctness of the trajectorizing algorithm, an optical motion capture system was also used to record the same motions. Results showed that the proposed motion tracking system measured the elbow joint angles of the flexion-extension motions with high consistency with the measurements obtained from the optical motion capture system. Statistical analysis showed that joint angles between two systems are highly correlated. The error of elbow joint angles measured by our system yielded small root mean square error (RMSE) and small median absolute deviation (MAD). These results suggest that an IMU-based (more specifically, a gyroscope-based) motion tracking system can be realistically used to accurately track a patient's motion without the need of numerous sensors or an overly complicated set-up.

Keywords: Healthcare; Motion tracking; Wearable wireless sensor

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1. Introduction

National health care spending in the United States is estimated to reach $4.8 trillion in 2021, which will consume nearly 20% of GDP (Centers for Medicare and Medicaid Services, National Health Expenditures Projections 2011-2021) [1]. The applications of wireless wearable sensors reduce healthcare costs and grant users flexibility and mobility [2]. In the past decade, there has been a rising interest in wearable sensor-based monitoring systems within the healthcare domain. Various publications have investigated healthcare systems focusing on monitoring physiological activities and motions. Typical hardware devices used in these systems employ the use of computers [3], mobile devices [4,5,6], and a wide range of sensors (heart rate monitor, blood pressure, body temperature, electrocardiogram (ECG), electromyogram (EMG), respiration monitor, accelerometer, gyroscope, etc.) [7,8].

Most of the healthcare systems were designed for different types of patients based on age, disease type, biological signals measured, and other factors. Target users of previous healthcare systems included patients, doctors, therapists and others. For example, Lee et al. developed a healthcare monitoring system for elderly clinical and trauma patients [9], Navarro et al. designed the monitoring system for elderly and infirm patients [10], and Suryadevara et al. integrated a wearable sensor-based healthcare system to monitor health perception and daily activity behavior for the elderly [8].

Motion tracking techniques are applied in many fields, ranging from animation [18] to clinical applications [3,6]. Current sensor-based motion tracking systems use a variety of sensors aimed to monitor the motion patterns of a patient. Although there are other motion tracking systems on the market (e.g., Xsens [18]), our motion tracking system is low cost, marker-free, and easy to install and use. Generally, gyroscope and accelerometer data are combined to determine the pose (orientation and position) of a tracked body segment, modeled as a rigid body [11]. Aside from the extra power consumed from continuously sampling multiple sensors, using an accelerometer can produce extra sources of errors, primarily because the accuracy of the measured acceleration is highly sensitive to the accuracy of the measured rotation. It was also necessary to correctly measure the location of the sensors on the body in these studies. In addition to the gyroscope and accelerometer, motion tracking systems may use other sensors such as magnetometers to calibrate the orientation of the sensor which can further increase the cost of these systems. To avoid these issues, the wearable sensor-based motion tracking system introduced in this paper minimizes the types of sensors used and is capable of calibrating without the need of additional equipment, performing additional anthropometric measurements, or measuring the location of the sensors.

This paper is structured as follows: Section 2 outlines our IMU system, experimental set-up, and the algorithm used to extrapolate the upper limb motion from IMU data. In Section 3, the experimental procedure and the method of analyzing the data is described in detail. Section 4 presents the results and discusses the findings. Lastly, Section 5 explains the significance of the research and describes its potential for further investigation.

2. Development of the wearable motion tracking system

2.1. Overview

We developed an upper limb motion tracking system using three low-cost SensorTag wireless sensor units from Texas Instruments. The onboard IMUs were used to track the upper arm and forearm, transmitting the sampled data via the device's Bluetooth module. The SensorTag uses the IMU-3000 gyroscope by InvenSense. Each gyroscope was set to a range of ±250 degrees per second with a sampling frequency of 50 Hz, which is sufficient to track a subject's motion with high accuracy. The SensorTag uses the KXTJ9 acceleromter by Kionix. Each accelerometer has its range set to ±4 G and its sampling rate set to 5 Hz. The bluetooth module used on the SensorTag is the CC2541 by Texas Instruments. It complies to Bluetooth Low Energy (BLE) specifications which was developed to address the need for robust wireless communication under low power settings with a focus on consumer and healthcare applications [12]. With this set-up, it is possible to use a Bluetooth enabled laptop to connect to and gather data from multiple SensorTags simultaneously.

To validate the accuracy of our system and model, we used the OptiTrack System, a commercially available, marker-based, optical motion capture system by NaturalPoint. It uses a Velcro suit to which 36 retroreflective markers were attached. These markers were tracked by 12 specialized cameras equipped with infrared LEDs. Fig. 1 outlines the underlying principle guiding the experiment through which our system's accuracy will be assessed. The

OptiTrack system produces joint trajectories with a temporal resolution of 100 Hz and a spatial resolution of 1 millimeter [13].

The Velcro suit also offers a means for attaching the IMU units to the subject as shown in Fig. 2 (a). A chest IMU was also used during the motion capture recording, but data collected from it was not used in the data analysis. A video camera was set up to record the subjects' motions. This was implemented in order to facilitate time synchronization between the IMU and the OptiTrack motion capture systems when processing the data. The set-up is shown in Fig. 2 (b).

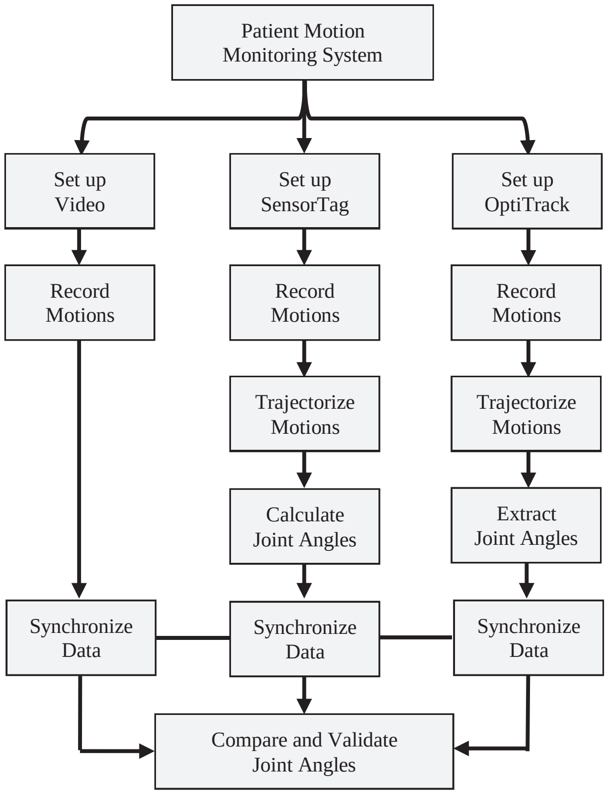

Fig. 1. System overview flowchart.

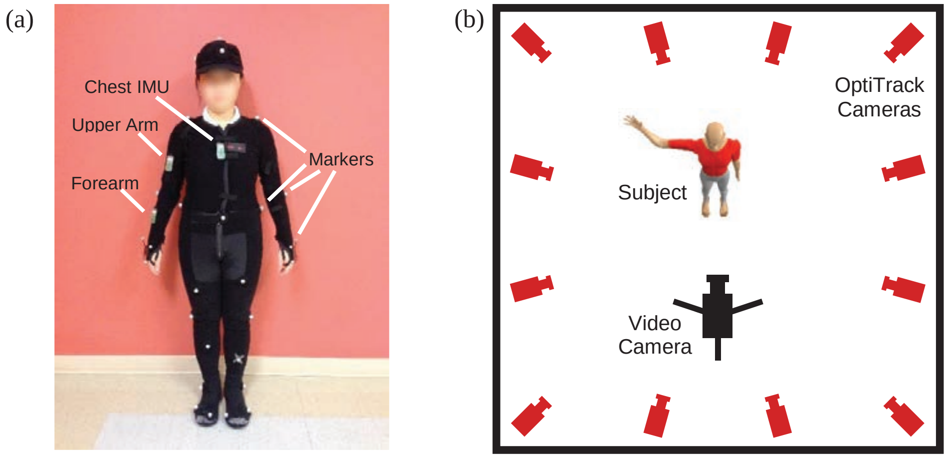

Fig. 2. Experiment set-up: (a) Subject wearing OptiTrack Velcro suit with markers and IMU sensors; (b) experiment layout with 12 OptiTrack cameras.

2.2. Tracking algorithm

The human body's posture can be fully described by knowing all of its joint angles. The data obtained from an IMU's gyroscope represent the angular velocity ($\boldsymbol{\omega_t}$) given in *x*-, *y*-, and *z*-rotation components with respect to the IMU's own reference frame. In order to calculate the sensor's angular displacement, these velocity samples can be chained together akin to mathematical integration. Due to the high sensitivity of the accuracy of the orientation (angular position) to sampling error, we use quaternions to represent rotations instead of Euler angles since the latter contain points of singularities [14]. These singularities are equivalent to the phenomenon of gimbal lock and any small error in measurement or rounding near these points will be magnified immensely, yielding poor estimations of orientation.

By knowing the sampling time interval (Δt), we can calculate the quaternion representing angular displacement between samples as shown in (1).

$$r_{S_{t-1}}^{S_t} = \cos\left(\frac{\theta_t}{2}\right) + sin\left(\frac{\theta_t}{2}\right)\,(\omega_{tx}i + \omega_{ty}j + \omega_{tz}k) \tag{1}$$

Where $\theta_t = |\omega_t|\Delta t$ denotes the angle step, script *S* denotes the sensor frame, subscript *t* is the current time step, and *i*, *j*, and *k* are the quaternion basis elements. In this convention, r_a^b is the rotation quaternion describing the orientation of frame b with respect to frame a. The process of trajectorizing the sensor's orientation can be achieved as follows:

$$r_{S_0}^{S_t} = r_{S_0}^{S_1} \cdot r_{S_1}^{S_2} \cdot \ldots \cdot r_{S_{t-1}}^{S_t} \tag{2}$$

Here, $r_{S_0}^{S_t}$ represents the orientation of the current sensor frame (S_t) relative to the initial sensor frame (S_0). Since the orientation of the IMU relative to the subject's limb is arbitrary or unknown, a calibration step needs to be performed to relate the two. While a multitude of calibration methods are described throughout the literature which rely on additional sensors [15,16], we developed a unique calibration process that only requires the subject to perform a known, specified motion recorded using only the gyroscope and the accelerometer. The subjects were instructed to hold a neutral stand posture with the arm pointing straight down. In this posture, the SensorTag's accelerometer was used to detect the direction of gravity. Next, the subjects were asked to flex their shoulder while keeping the elbow fully extended. These motions are sufficient to determine the orientation of the arm with respect to the world and the orientation of the IMU with respect to the arm. The elbow joint angle can be calculated by knowing the orientation of the forearm and upper arm in space.

3. Method

3.1. Subject

Eight healthy adults (4 female, 4 male, age 22 – 28 years) participated in the experiments. The average height was 169.69 cm (SD = 10.14 cm). All of the subjects were right-handed. None of the subjects had any previous upper limb injuries.

3.2. Experiment procedure

After setting up the video camera and the 12 OptiTrack cameras surrounding the recording arena, subjects were asked to don the OptiTrack motion capture suit and cap. Next, the 36 retroreflective markers were attached according to the OptiTrack's marker guide. Three SensorTags were then fastened to the body as depicted in Fig. 2 (a) – one to the forearm, one to the upper arm, and one to the chest – using the suit's Velcro fabric. The suit is elastic, designed to conform to the user's body while preventing attached markers from slipping. This feature was also exploited to rigidly secure the IMUs to their respective body segments. The IMUs were powered on, and a PC with a BLE host dongle (BLED112 USB Bluetooth dongle from Bluegiga) was used to connect to each sensor.

All motions that each subject had to perform were first described to them before data collection began. To maintain consistency between subjects, the motions that each subject had to perform were presented in front of them by a demonstrator so that they could simply mirror the motions. At the beginning of each recording session, the first motion that the subjects performed was a rapid abduction-adduction of the shoulder. This motion allows for easy identification of the exact frame of highest arm elevation in the IMU and OptiTrack data. This helps to synchronize the measurements between the two systems. Subsequently, the IMU calibration procedure was executed as described in the tracking algorithm. Next, repeated elbow flexion-extension motions were performed as depicted in Fig. 3. Each recording session consisted of ten such cycles.

3.3. Data collection and analysis

During the experiment, eight subjects were asked to perform ten elbow flexion-extension cycles as described above. Data from our motion tracking system and OptiTrack motion capture system were recorded. The trajectorization algorithm was used to obtain the elbow joint angles. To validate our motion tracking system, the trajectorized data of the IMU system were compared to those of the OptiTrack system.

To evaluate the similarity between measurements of our system and OptiTrack system, correlation coefficient (CC) analysis was used. Root-mean-square error (RMSE) was calculated to indicate the difference of joint angles between the two systems [16]. As a scale for how much the difference in angle is distributed, the median absolute deviation (MAD) was calculated.

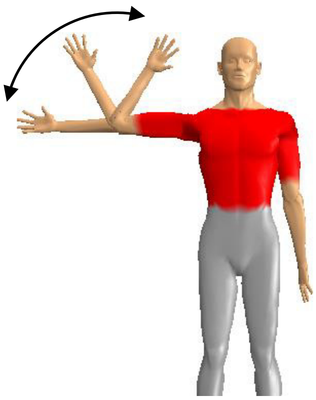

Fig. 3. Elbow flexion-extension motion.

4. Results and discussion

The results showed that our motion tracking system measured the elbow flexion-extension (joint angles) with high consistency to those of the OptiTrack. Fig. 4 shows the results of all subjects obtained from our IMU system and from the OptiTrack system.

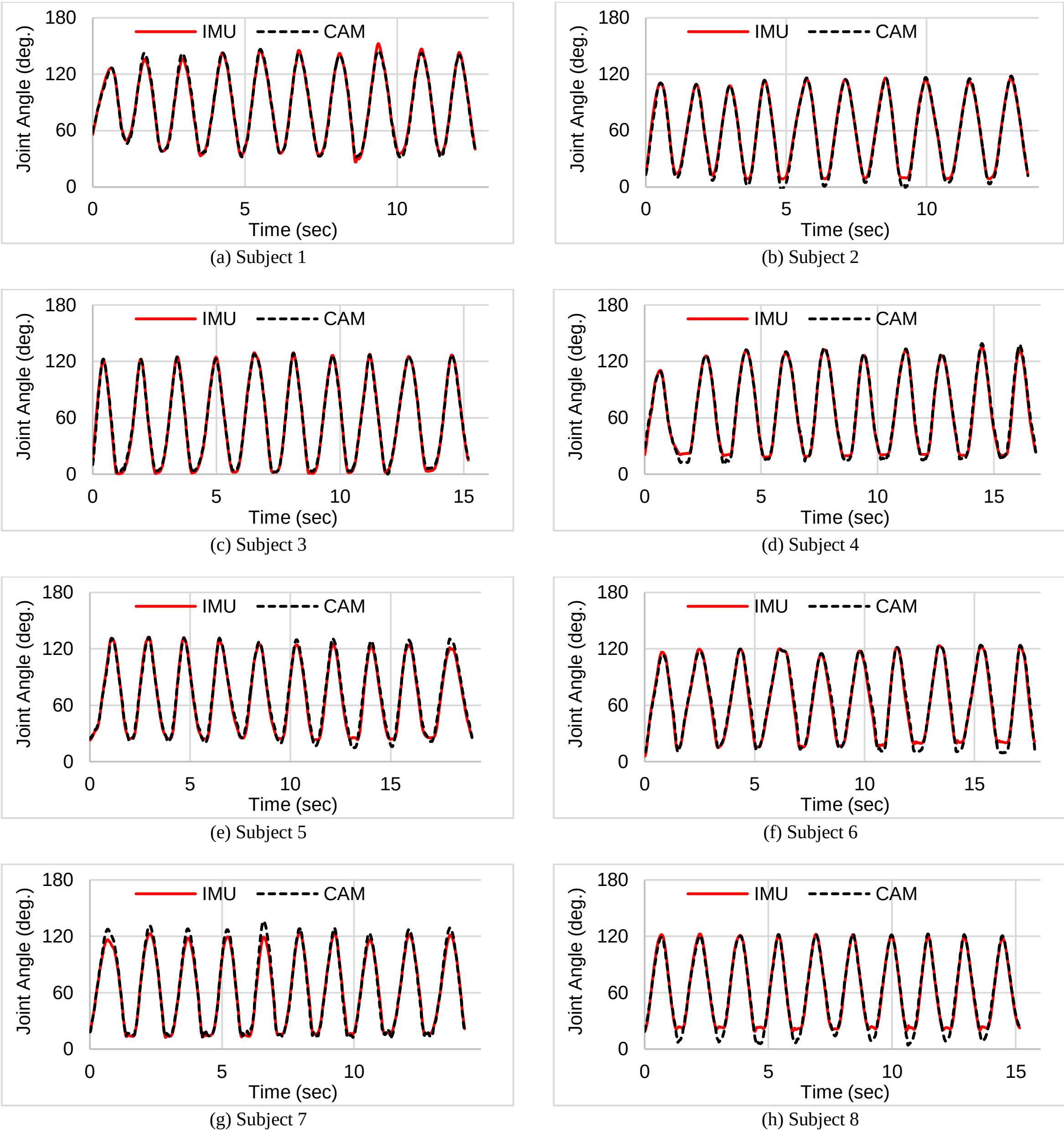

Fig. 4. Elbow flexion-extension motion.

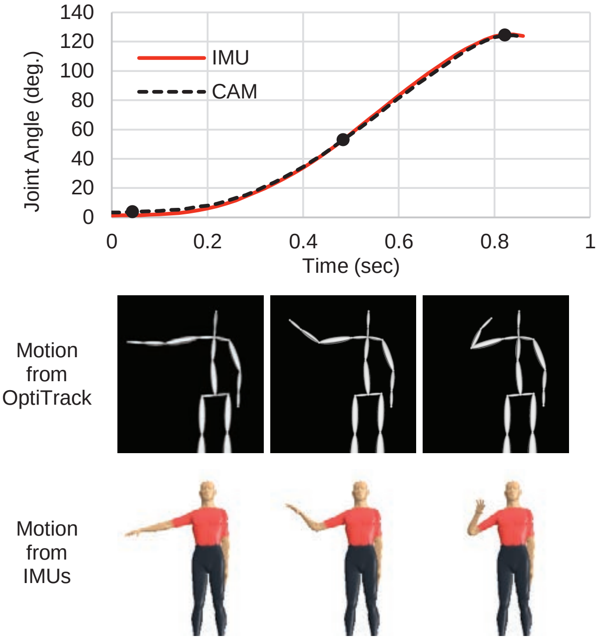

Fig. 5. Joint angle and visualization of an elbow flexion motion.

Fig. 5 shows a single flexion motion for one subject with a visually recreated representations of three key frames of the motion. For the joint angles measured from the two systems, results of eight subjects are shown in Table 1. The correlation coefficient (CC) for joint angles of two systems was high (> 0.99 for all subjects). The high CC presents a strong correlation between two data sets. RMSEs for all subjects were low (2.06° – 5.53°). Also, MADs between measures from two systems were low for all subjects (2.21° – 3.47°).

Table 1. Results for all subjects.

Subject	1	2	3	4	5	6	7	8
CC	0.99	0.99	0.99	1.00	1.00	0.99	1.00	0.99
RMSE (°)	2.46	3.14	2.06	3.07	3.87	4.01	4.53	5.53
MAD (°)	2.21	2.62	2.23	2.38	3.22	2.69	3.47	3.12

In previous motion tracking studies, Zhou et al. obtained CC values between 0.96 – 0.98 and RMSE values between 2.5 – 4.8° from their upper limb motion tracking system [16]. Takeda et al. estimated gait posture using accelerometer and gyroscope sensors obtaining CC values from 0.72 to 0.92 and RMSE from 4.9 – 8.7° for hip and knee joint angles [17].

Compared to previous studies, our system is able to provide quantitative measurements of elbow motion with relatively high accuracy using wearable sensors. Moreover, due to the simplicity of the presented system with regards to the number of types of sensors used and the ease of donning the sensors, our IMU motion tracking system provides notable advantages over previously developed systems. The readily available hardware and software permit this system design to be a practical solution for any limb motion monitoring system.

5. Conclusion and future work

In this study, we developed a wearable, sensor-based motion tracking system and elbow joint angles of eight subjects were tracked using two IMUs attached to the upper arm and forearm. A motion trajectorization algorithm was developed that is able to calculate elbow joint angles. This algorithm can be used with arbitrary placement of the IMUs as long as each IMU is placed on the appropriate limb. Thus, no manual anthropomorphic measurements need to be performed. Results of the elbow flexion-extension experiment yielded results consistent with that of the optical motion tracking system. Specifically, the IMU-based tracking system and the camera-based tracking system yielded RMSE values between 2.06° and 5.53°. These results suggest that a gyroscope-based motion tracking system can be realistically used to accurately track a patient's motion without the need for numerous sensors or an overly complicated set-up.

In our experiment, we only used data from two IMUs to track the elbow joint angle for some simple motions for one arm. We plan to expand our system to incorporate more IMUs to track more body parts and joint angles. Regarding system applications, we also plan to integrate our motion tracking system with advanced kinematic modeling software, such as OpenSim which can further aid in processing, visualizing, and analyzing patient motions to aid in physical rehabilitation.

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